PRINCE

Theory and Performance of

a High Frequency Converter

Electrical Engineering

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THEORY AND PERFORMANCE

OF A HIGH FREQUENCY CONVERTER

BY

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THESIS

FOR THE

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IN

ELECTRICAL ENGINEERING

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

DAVID CHANDLER PRINCE

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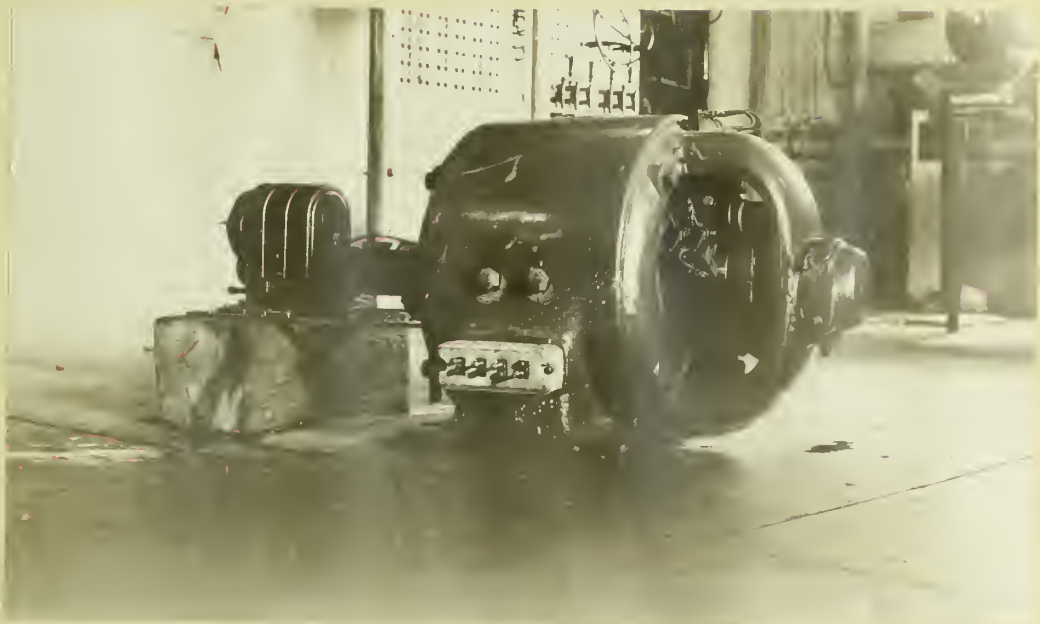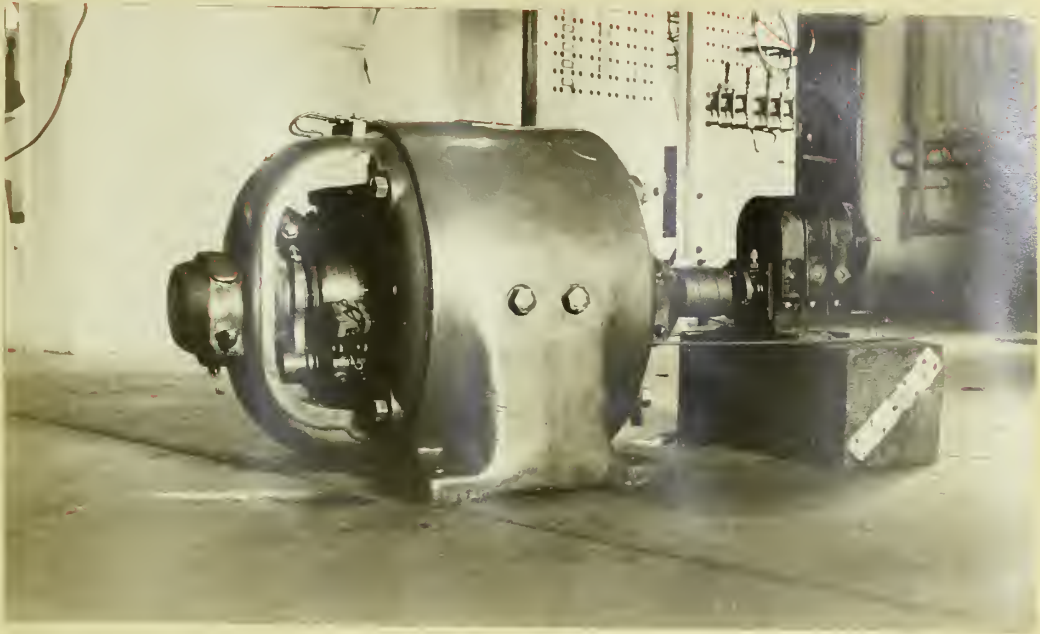*N. F. Schaller*
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Table of Contents.

General Electric High Frequency Converter.

(Magneto for speed indication attached.)

Theory and Performance of a High Frequency Converter.

I   Introduction.

The new high frequency converter introduced by the General Electric Company operates by virtue of the fringing and tufting caused by the armature teeth as they pass across the field poles.

Embedded in the direct current field pole faces of an ordinary two pole motor there is a winding which has a pitch equal to the tooth pitch of the armature.   As the latter revolves,alternate zones of a greater or lesser flux density succeed each other across the face of the pole. These lines of force cut the embedded high frequency winding inducing an E.M.F.which has a frequency equal to the product of armature teeth and revolutions per second,that is,equal to the slot frequency of the machine.

In order that this scheme may work effectively the pole shoe must be laminated,the air gap rather small and the tooth density low.   This last requirement is the most important since the difference in reluctance between the path through the armature teeth and the path through the slot is entirely responsible for the electromotive force induced.

If the air gap were not small,the spread of flux from the teeth would practically neutralize the difference in reluctance between tooth and slot. The flux density in the field pole shoe varies at high frequency when the machine is in operation so that this shoe must be laminated in order to prevent excessive eddy current and hysteresis loss. Also the effect of any eddy currents would be to obstruct the

lines of force and prevent their penetrating a sufficient
distance into the pole iron.

II General Theory and Development of the E.M.F. Formula.

In order to discuss the operation of this alternator
quantitatively,it is necessary to make a number of approx-
imations,the accuracy of which is rather problematical.
The amount of tufting from the armature teeth must be es-
timated,while the damping action of the eddy currents and
hysteresis action in the pole tips can only be guessed at.

Let the magneto motive force of the field be $\mathcal{H}'$. Then,
refering to Fig.1.,the density of the flux at b due to lines
traveling from b to a will be

$$\frac{\mathcal{H}'}{ab} = \frac{\mathcal{H}'}{\sqrt{h^2 + (S/2)^2}}$$

The density due to lines traveling from b to c will be

$$\frac{\mathcal{H}'}{ac} = \frac{\mathcal{H}'}{h+d}$$

Of course some flux will leave the iron at points between a
and c ;on the other hand,most of the flux from a will tend
to go straight across the gap to the iron of the pole shoe;
so that,by considering only the lines from a and c a fair
approximation should be obtained. Then the total density
at b is

$$\frac{\mathcal{H}'}{\sqrt{h^2 + (S/2)^2}} + \frac{\mathcal{H}'}{h+d}$$

The density over the tooth face will be

$$\frac{\mathcal{H}'}{h}$$

and the field will have some somewhat the appearance of Fig.2
The E.M.F.wave produced by conductors cutting such a field
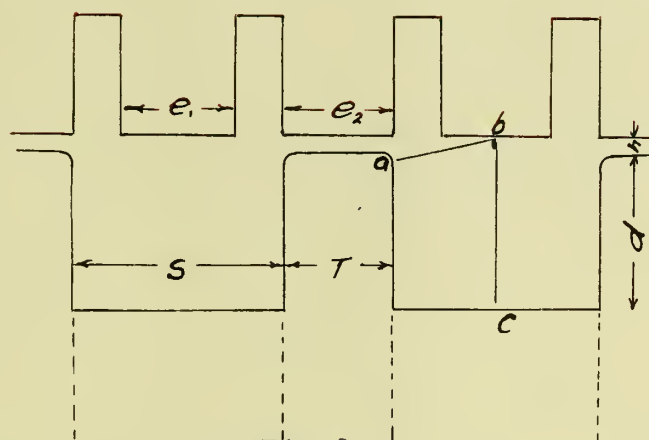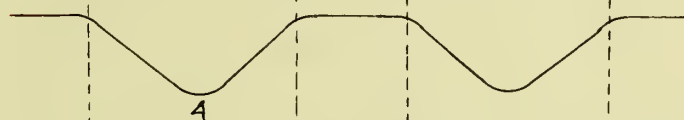is shown by the same figure. At any one time half of the
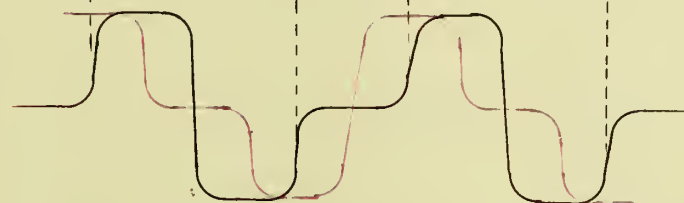
Fig.1.

Diagram of Teeth and Pole Face.

a)

b)

Fig.2.

a) Flux Distribution.

b) E.M.F. Wave.

conductors are lying in the uniform field over the tooth faces. These conductors are, instantaneously, producing no E.M.F., as shown by the curve opposite this position. Midway between these conductors is the other set whose E.M.F. is shown by the red line on Fig.2. The terminal voltage is the sum of these two. As the curve of flux density can have no square corners, the resulting E.M.F. wave should be nearly a sine wave.

The density over the tooth face is:

$$\frac{\mathcal{H}''}{h} = M$$

The minimum density at point 4. Fig.2. is

$$\mathcal{H}''\left(\frac{1}{\sqrt{h^2 + (S/2)^2}} + \frac{1}{h+d}\right) = O$$

Then the mean change of density which induces the E.M.F. is

$$M - O$$

Let L be the length of the armature iron parallel to the shaft. The flux in the area e_1 is

$$e_1 \times L \times M$$

That in e_2 is

$$e_2 \times L \times \frac{M+O}{2}$$

The induced E.M.F. per conductor is

$$E = \frac{2.22 \times f \times e \times L}{10^8}\left[M - \frac{M+O}{2}\right]$$

Or, if N is the total number of active conductors which is equal to the total number of turns, the voltage for the whole winding is

$$E = \frac{2.22 \times f \times N \times e \times L}{10^8}\left[\frac{M - O}{2}\right]$$

The E.M.F. of the machine is now accounted for in terms of values which are readily found.

6.

In the above formula the symbols represent:-

2.22 the conversion factor between average and effective values.

N the total number of turns on the machine.

e the peripheral length of the stator tooth face.

f the slot frequency i.e. R.P.S. x Teeth.

L the iron length parallel to the shaft.

$M = \dfrac{\mathcal{H}'}{h} = \dfrac{4\pi N_f I_f}{10\,h}$ where $N_f I_f$ is the field ampere turns per pole.

$O = \mathcal{H}'\left(\dfrac{1}{h^2+(S/2)^2} + \dfrac{1}{h+d}\right)$ $\mathcal{H}' = \dfrac{4\pi N_f I_f}{10}$

The parenthesis is defined above.

$\dfrac{M-O}{2}$ the mean flux variation

E the total E.M.F. induced.

Let us now apply the formula to the case in hand and find whether or not the approximation is sufficiently close to be useful.

Net iron length	L	3.25"
Width of stator tooth	e	.15"
Width of armature tooth	S	.36"
Depth of armature slot	d	.65"
Field turns per pole	N_f	2750
High frequency turns per pole	N	36
Frequency	f	2000
Air gap	h	.037"

$$\frac{M-O}{2} = \frac{4\pi N_f I_f}{2\times 10}\left[\frac{1}{h} - \left(\frac{1}{\sqrt{h^2+(S/2)^2}} + \frac{1}{h+d}\right)\right]$$

$$= \frac{I_f \times 2750 \times 4\pi}{2\times 10\times 2.54}\left(\frac{1}{.037} - \frac{1}{.18} - \frac{1}{.687}\right)$$

$$E = \frac{2.22\times 2000\times 72\times 2750\times 4\pi\times 20\times .15\times 3.25\times 2.54\, I_f}{2\times 10\times 10^8} = 130\, I_f$$

III Saturation Coefficient.

The curve from this equation is obviously a straight line, however, it follows the experimental E.M.F. curve as far as the knee of the latter. The bend in the experimental curve is, of course, due to saturation of the iron which has not been taken into account in the preceding derivation at all. It is a very simple matter to introduce a correction term in the form of a "saturation coefficient" which will cause the derived curve to follow the experimental curve over the entire working range of the machine with considerable accuracy. This saturation factor is derived from the direct current saturation curve for the machine operated as a generator as follows:- Taking the D.C. saturation curve of the machine as a measure of the saturation, the air gap density is to the density for no saturation as the ordinate of a point on the curve is to the ordinate of the corresponding point on a line tangent to the saturation curve through the origin; that is, OA/OB (Fig.3.) x density, considering no saturation, is equal to the density with saturation taken into account. Again $\frac{M-O}{2}$ will be found to vary with the same factor so that the induced E.M.F. E varies as this factor squared or as $(OA/OB)^2$. Applying this factor gives a curve for E which follows very closely the experimental curve of the machine. The final formula for the open circuit voltage is E= 130 $K^2 I_f$ where K=OA/OB for the value of field current used. The D.C. saturation curve and the derived and experimental A.C. saturation curves are shown in Figs.3-4.

IV E.M.F. Due to Armature Current.

It might seem at first thought that the armature current would directly effect the E.M.F. induced in the high frequency windings.   A little consideration,however,will serve to show that this is not the case. A movement of the brush contact from one commutator bar to another might be expected to displace the armature reaction over a small angle and thus induce an E.M.F. in a stationary winding cut by the reaction flux.   This effect may exist but is negligible for two reasons. The highest magnetomotive force of armature reaction is opposite the space between field poles.   The conductors on the machine used do not lie in such a flux. Commutation with wide carbon brushes almost entirely eliminates any tendency toward oscillation of the armature field.

V Effect of Direct Current Armature Reaction on E.M.F.

The ways in which the direct current armature reaction might affect the high frequency E.M.F. are two. Distortion of the field flux might cause saturation of one pole tip, thus reducing the flux and hence the induced voltage. The back ampere turns of the armature due to brush lead might reduce the total flux and so lower the voltage of the high frequency winding.

The total conductors in the machine tested were 320 lying in forty slots.   As the winding pitch was eighteen slots, the conductors in four slots did not have any effect on the armature reaction. This makes the conductors available for armature reaction 288 or 144 turns.   However,the conductors

lying in slots under the pole face,only,are available
for sending flux through the pole tips. There are twelve
slots under a pole giving ninety six turns to send this
flux. With a current of twelve amperes we have 1152 ampere
turns in this position. With normal field current there are
3300 field ampere turns so that the cross magnetizing ampere
turns are 33% of the total. This effect is present at the
extremities of the pole tips. It decreases to zero at the
center of the pole face so that the average result is about
16% in change of ampere turns. As actually operated the
brush lead is about five degrees so that the demagnetizing
action due to twelve amperes current in the armature is 173
ampere turns or about 5% of the total ampere turns. Adding
the cross magnetizing,demagnetizing and field ampere turns
vectorially gives a total of 3330 ampere turns acting upon
the pole shoes. This is in excess of the normal ampere
turns by only 1%. In making the addition,the demagnetizing
ampere turns were subtracted directly from the normal
field while the cross turns were added at right angles.
Actual test data shows a variation of about this amount,at
normal saturation,in the induced voltage,as shown in Fig.6.
Probably the averaging of the cross magnetizing action
across the pole gives too low a result but the whole effect
of the armature reaction is too small to warrant a more
careful calculation.

VI Effect of Alternating Current Armature Reaction
on Induced E.M.F.

Since there are twenty four slots across the face of one
pole shoe,there are twenty four poles of alternate sign pro-
duced by the high frequency currents. The resultant of all
the magnitomotive forces set up by these currents in the
direction of the main field M.M.F. is zero or,at most,a very
small alternating force which will have zero effect upon the
main flux. For this reason there can be no alternating
current armature reaction in the true sense of the word.
The result of the high frequency currents is merely to
produce screening,that is,they tend to prevent a rapid
change of flux across the pole face. This action can best
be dealt with by considering it as a leakage reactance. The
leakage lines around the conductors,superimposed upon the
main field of variable density produce a resultant field of
more uniform density. The E.M.F. produced by the cutting
of this field by the A.C. conductors is equivalent to the
full E.M.F.,considering no current,minus an E.M.F. of self
induction produced by the leakage lines around the conductors.
Under test the self inductive reactance,as found by passing
alternating current through the windings and measuring the
resistance and impedance drops, and the synchronous imped-
ance,as obtained by a short circuit test,came out almost
the same. This method of considering the reaction,then
seems entirely justifiable. The regulation of the machine
can be completely calculated as for a transmission line
having the same resistance and reactance. The effect of
leading and lagging currents,also,can be foretold.

VII   Enumeration of Tests Run on Machine.

It did not seem practicable to separate the phenomena of the machine while operating it as a rotary;therefore,it was run as a generator to determine the various constants. In order to get the normal frequency of 2000 cycles,a speed of 3000 R.P.M. was required. To indicate the speed continuously during test a small magneto was coupled to the rotary shaft and the magneto current then led to a frequency meter. In this way the frequency of rotation could be read at all times.

Tests were run with the rotary belt driven to detrmine:

a) The direct current saturation curve.

b) The alternating current saturation curve.

c) The synchronous impedance.

d) The effect of armature current alone in producing
E.M.F.

e) The effect of direct current armature reaction
on high frequency voltage.

Tests were run with the machine stationary to determine:

f) The high frequency winding resistance.

g) The high frequency winding impedance.

Great difficulty was experienced in running the rotary as a generator hecause of the high rotative speeds. Tests a,b,c,and d were finally run off at normal frequency by taping the pulley with friction tape and using the highest practicable belt tension.   Test e could not be run at normal frequency because the load on the D.C. side proved too heavy for the belt friction.

VIII Index to Test Data and Curves.

Saturation Curve Data.

I_f	E_{DC}	E'_{DC}	E'	K	K^2	E'_{AC}	I''_f	E''_{AC}
.03	8	8	8	1	1	3.9	.04	8.0
.18	50	47	47	1	1	23.4	.10	18.2
.27	76	71	71	1	1	35.1	.11	19.4
.31	83	82	82	1	1	40.3	.12	20.4
.35	93	93	93	1	1	45.5	.13	22.5
.41	106	107	108	.99	.98	52.2	.17	27.8
.50	121	123	132	.93	.87	56.5	.20	33.2
.59	130	135	156	.86	.75	57.5	.25	37.7
.65	136	141	172	.82	.67	56.0	.28	42.0
.75	150	149	198	.75	.57	55.5	.32	46.3
.86	153	157	227	.69	.48	53.7	.36	50.0
.93	158	162	246	.66	.43	52.0	.40	52.9
1.04	167	168	275	.61	.37	50.0	.42	54.3
1.11	172	173	294	.59	.35	50.0	.52	57.9
1.20	178	178	317	.56	.31	49.0	.55	58.5
							.61	58.8
							.64	58.7
							.65	58.7
							.70	58.5
							.78	57.4
							.87	56.0
							.95	54.8
							1.04	53.3
							1.12	51.8
							1.16	51.1

I_f is the field current in the D.C. saturation test.

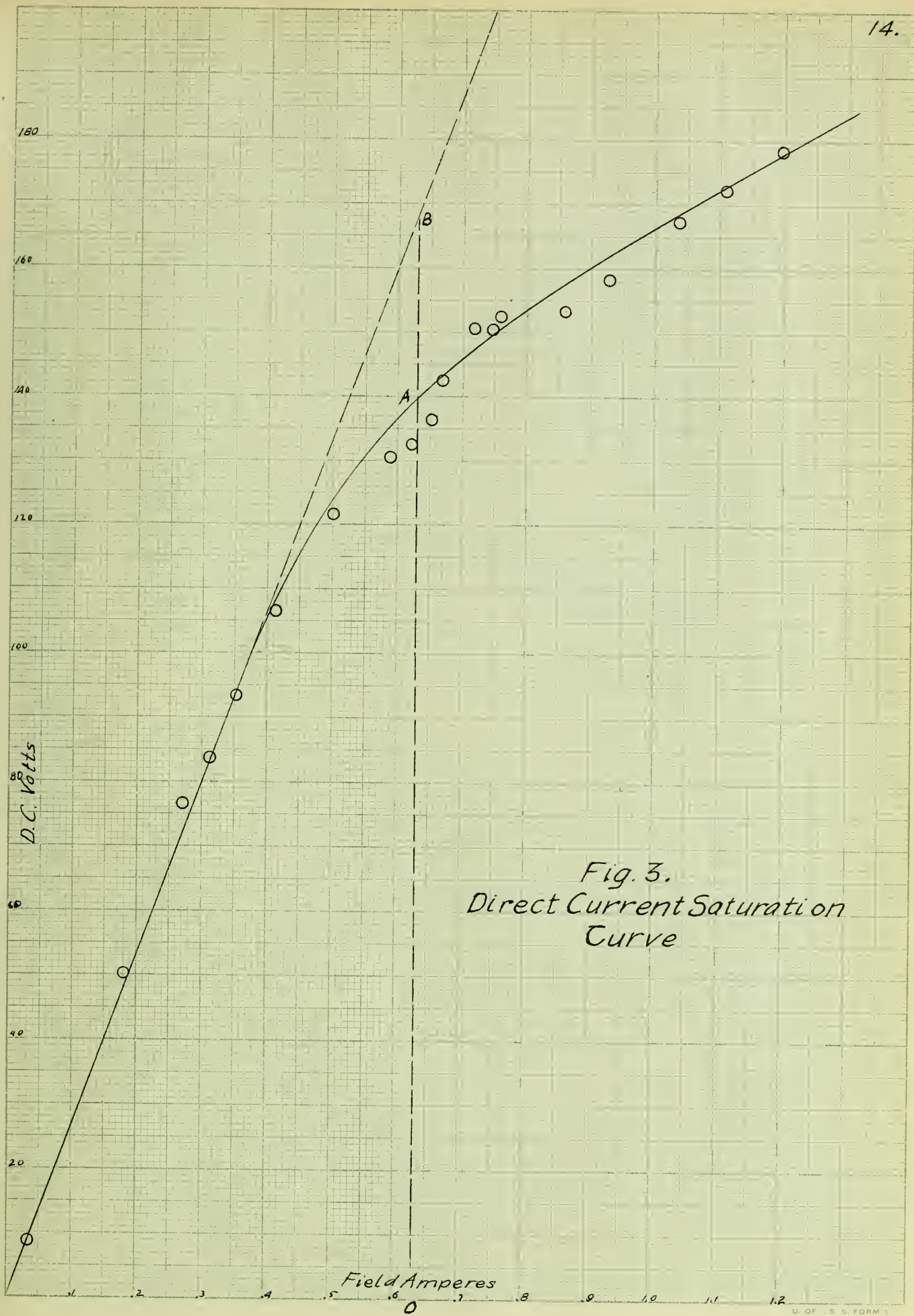E_{DC} is the E.M.F. from the D.C. saturation test.

E'_{DC} is the E.M.F. found by interpolating from the curve
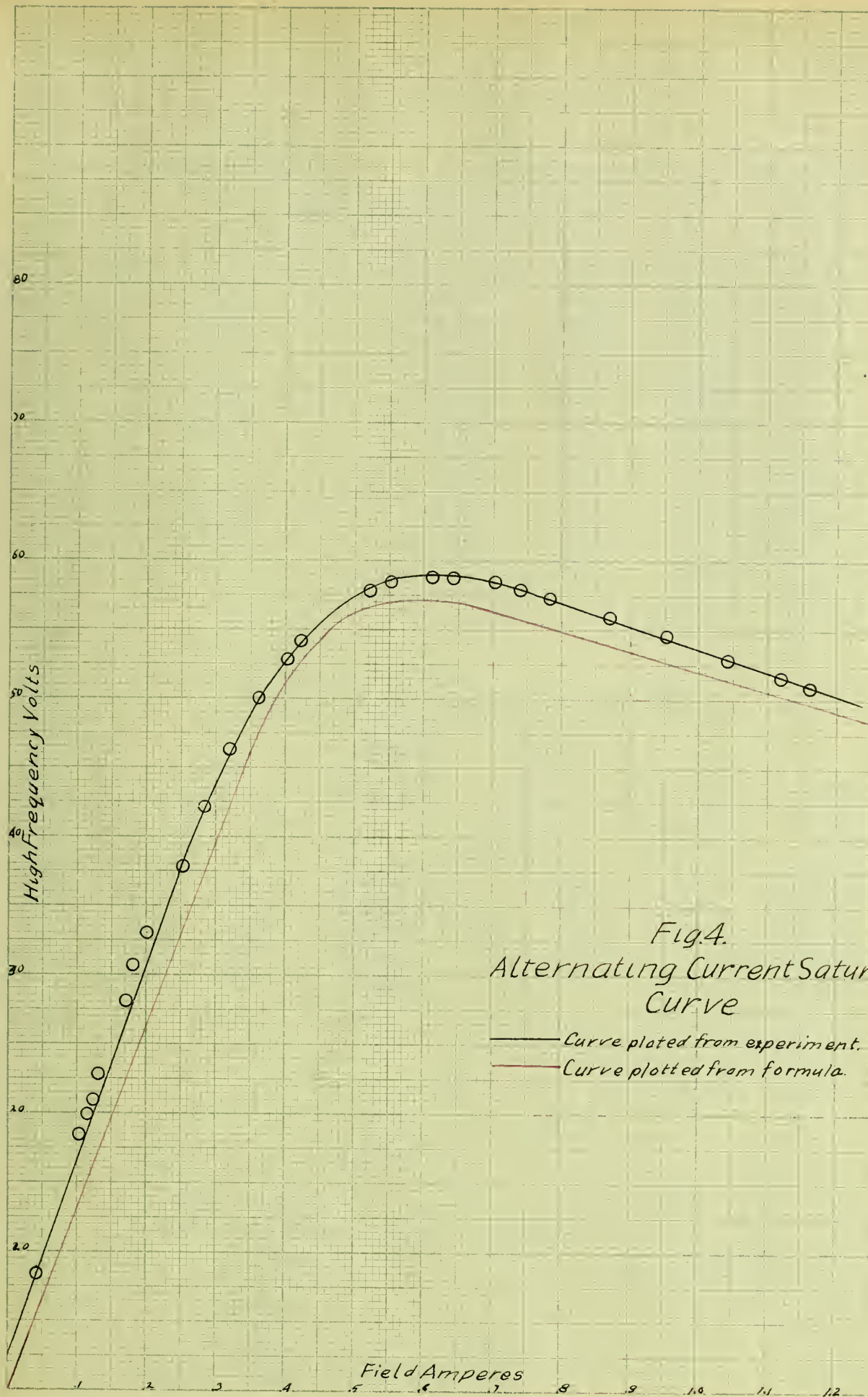between I_f and E_{DC}.

E' is the E.M.F. found by interpolating from the
tangent to the curve through the origin, Fig.3.

K is equal to E'_{DC}/E' or OA/OB, Fig.3.

I''_f and E''_{AC} are the coordinates of the experimental
A.C. saturation curve.

I_f and E'_{AC} are the coordinates of the derived
A.C. saturation curve.

Fig. 3.
Direct Current Saturation
Curve

14.

D.C. Volts

Field Amperes

Fig.4.
Alternating Current Saturation
Curve

———— Curve plated from experiment.
———— Curve plotted from formula.

Experimental Data.

Synchronous Impedance   Direct Current Armature Reaction.

I_f	I_{load}	Speed normal I_f= .6 amps		I_f= .3 amps.	
		I_{load}	E_{AC}	I_{load}	E_{AC}
.050	7.20				
.055	8.20				
.060	8.90	14.60	48.7	14.35	35.4
.070	9.92	15.00	48.7	13.30	35.5
.080	11.10	13.65	48.8	12.70	35.6
.095	12.90	12.25	49.0	11.90	35.7
.110	15.15	10.90	48.9	11.15	35.7
.135	18.20	10.40	48.9	10.20	35.8
.150	20.70	8.95	49.1	9.25	36.2
.180	24.30	7.55	49.0	8.50	36.2
.210	27.80	6.30	49.0	7.45	36.6
.230	30.60	5.05	49.1	6.75	36.5
.250	33.00	3.70	49.2	5.75	36.8
.270	35.40	3.30	49.2	4.50	37.0
		0.00	49.5	3.20	37.0
				2.65	36.8
				0.00	38.0

Resistance and Impedance at 60 Cycles.

Machine Stationary.

Direct Current in Winding   60 Cycle Current in Winding.

E.	I.	R.	E.	I.	Z.
.62	10.0	.0620	2.0	28	.0715
.85	13.7	.0620	3.0	40	.0750
1.28	20.5	.0625	1.9	25	.0760
2.17	35.0	.0620	2.3	31	.0740
2.40	38.0	.0630	2.9	38	.0760
	Mean	.0623		Mean	.0745

Fig. 5.
Short Circuitor Synchronus Impedance
Test

Armature Current.

Field Amperes

17.

Fig. 6.
Effect of Armature Reaction on
High Frequency Voltage

Field Current .6 Amperes

Field Current .3 Amperes.
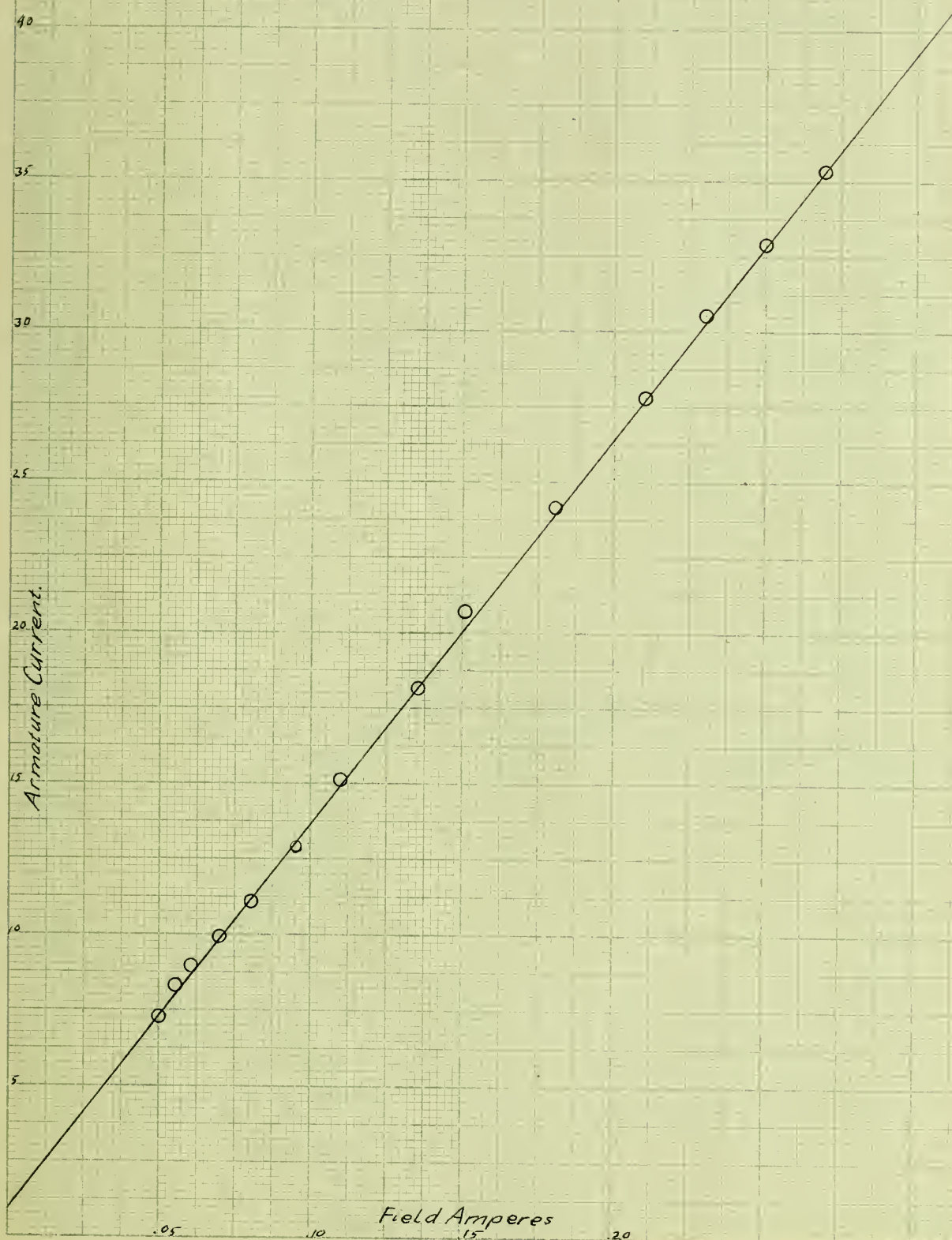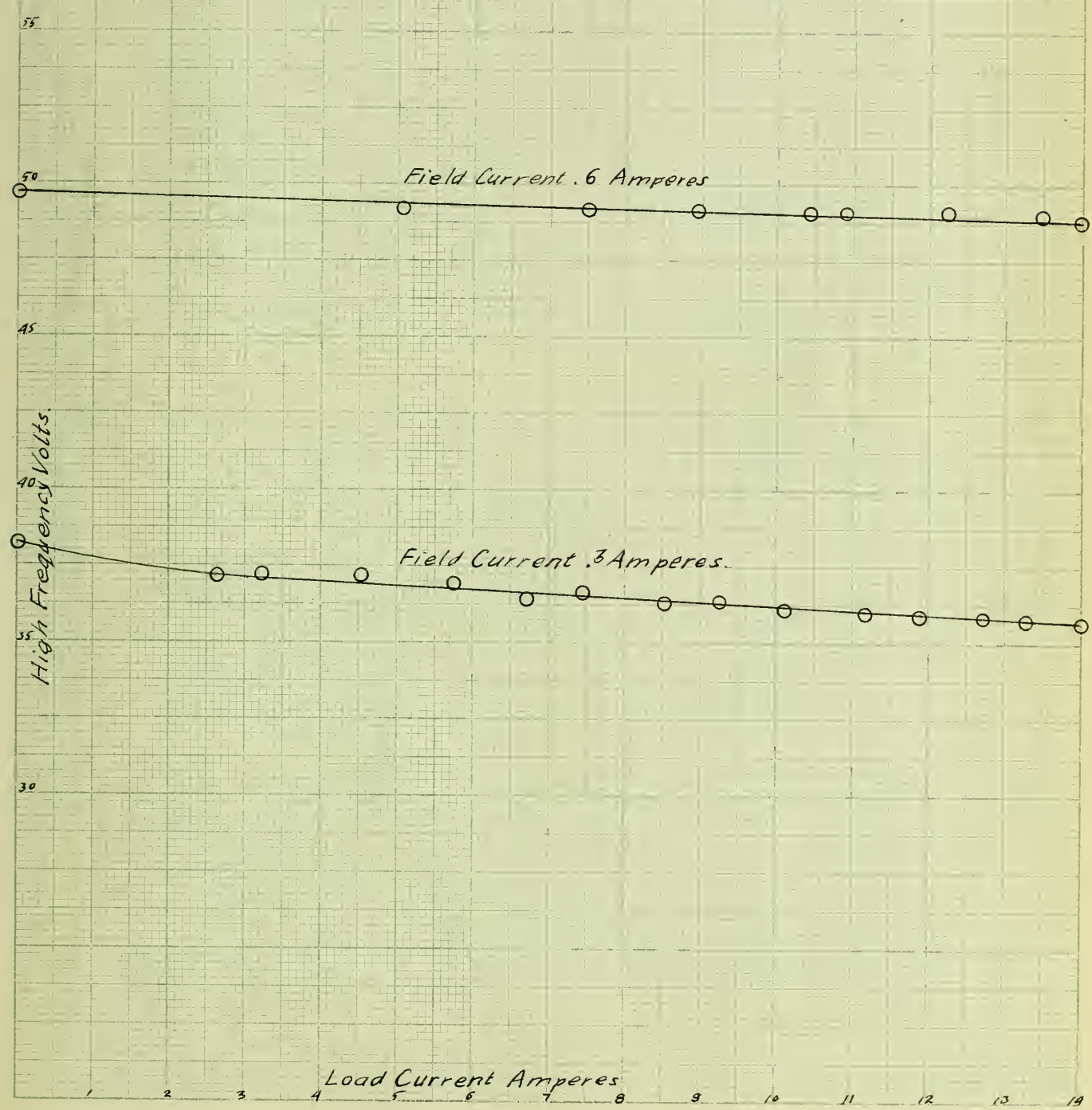
High Frequency Volts.

Load Current Amperes

IX   Winding Specifications.

Field Windings

      Size of Wire   28.5   mils bare

      Turns per Coil   2750.

      Resistance per Coil at 25 C   67.75 ohms.

Direct Current Armature

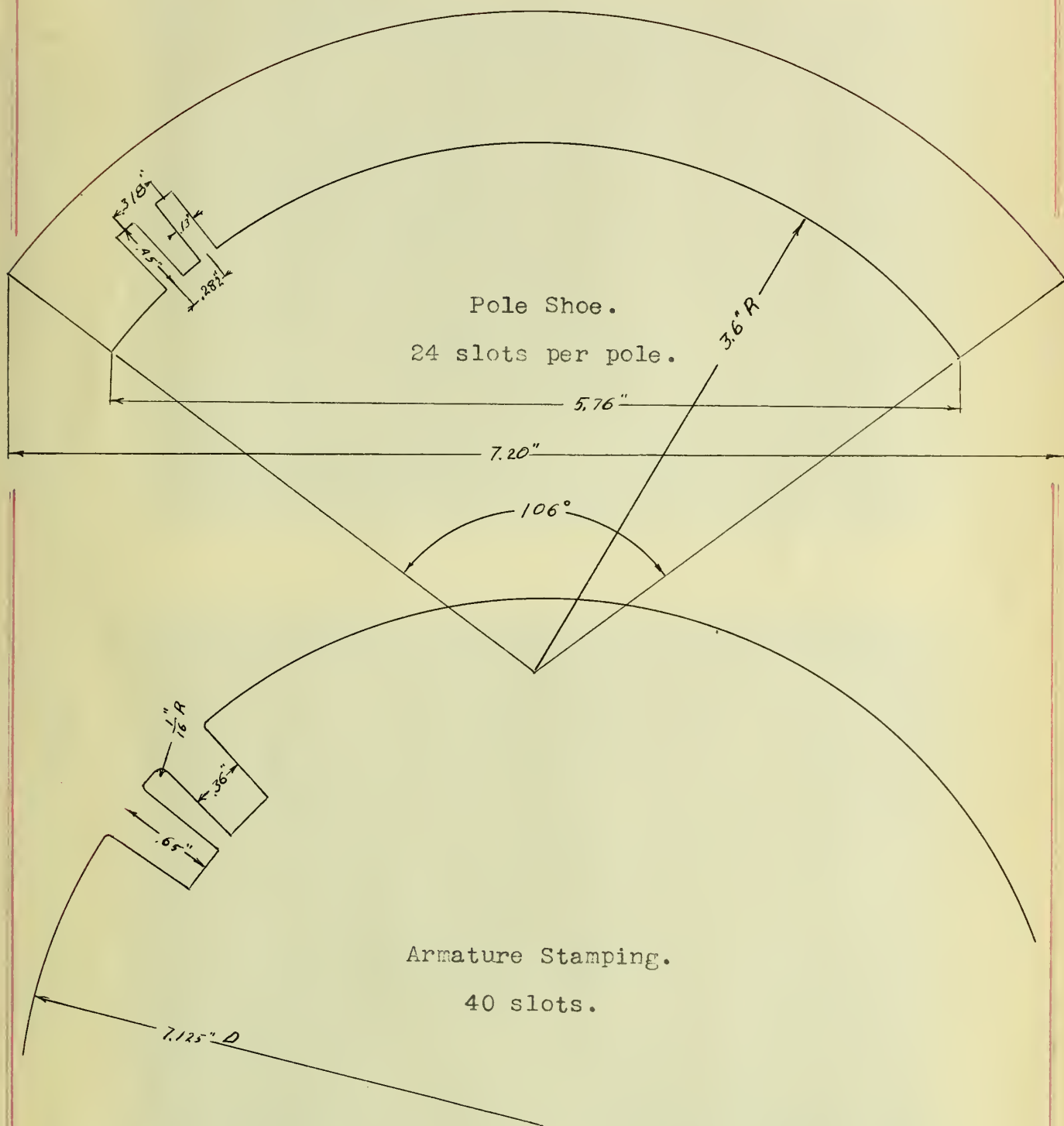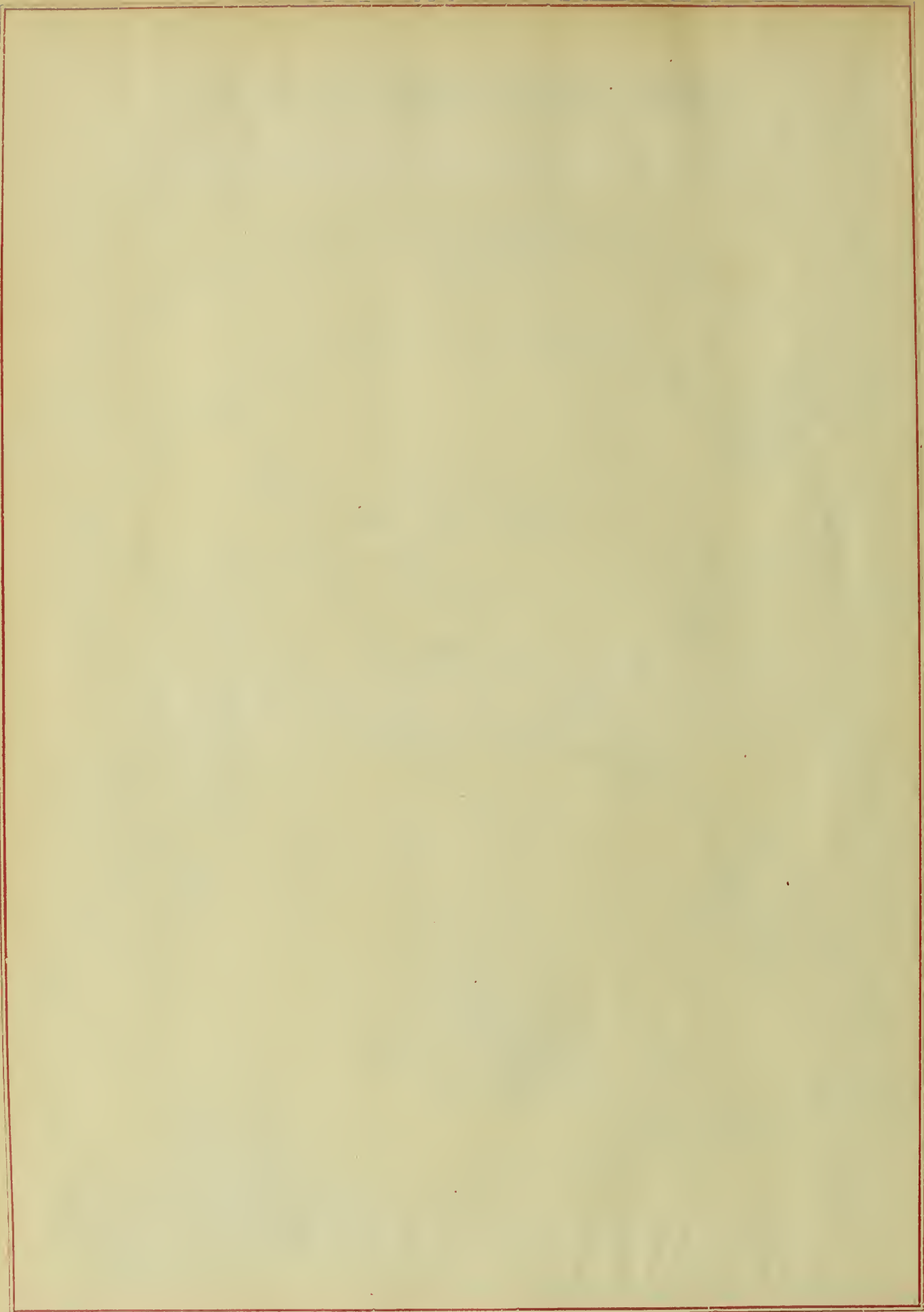   Size of Conductor   .091 D.C.C.

      Number of Slots   40.

      Conductors per Slot   8.

      Number of Coils   80.

      Turns per Coil   2.

      Number of Commutator Segments   80.

      Winding Pitch   18.

High Frequency Alternating Current Ainding.

      Size of Conductor   .1x.1 in.

      Number of Slots per Pole   24.

      Conductors per Slot   3.

      Type of Winding   Wave

      Total Turns   72.

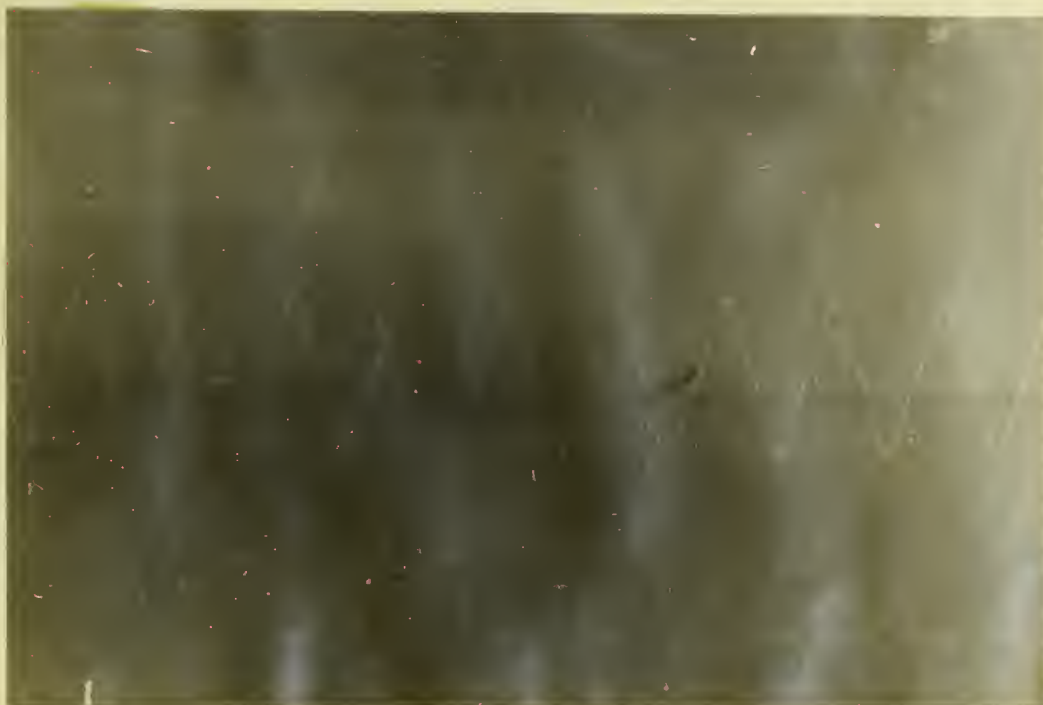   Turns per Pole   36.

Stamping Details of Armature and Pole Tip.

Pole Shoe.

24 slots per pole.

3.6" R

5.76"

7.20"

106°

.318"

.13"

.45"

.282"

Armature Stamping.

40 slots.

1/16" R

.36"

.65"

7.125" D

Oscillogram of E.M.F. Wave.

Normal Frequency, 2000 Cycles.

Quarter Frequency, 500 Cycles.